Radiowave Method of High Energy Neutrino Detection: calculation of the expected event rate

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Abstract

The sensitivity of an ice radiowave detector to the anticipated high energy neutrino fluxes is calculated on the basis of a detailed threshold analysis and computation of the shower production rate. We show that diffuse neutrinos from Active Galactic Nuclei could be detectable in a radio detector of 1 km^2 area established in Central Antarctica.

1 Introduction

About 30 years ago Askar'yan proposed a new method for the detection of high energy particles by means of the Cherenkov coherent radiowave emission from the negative charge excess of electromagnetic showers generated in air or dense media [1]. The charge imbalance of a shower is created by the Compton scattering of shower photons on atomic electrons, the annihilation of shower positrons in flight and the knock-on process. The percentage of negative charge excess amounts to $\sim 20\%$ at the shower maximum. The resulting Cherenkov emission by excess electrons is coherent at wavelengths larger than the shower lateral dimension, i.e. in the radiowave region. In spite of the very low frequencies compared with visible light, this emission should be observable for sufficiently high primary energy because the radiated power scales with the square of the shower size.

The radio pulses have been indeed successfully observed from air showers (EAS) in coincidence with particle arrays, but some their properties (polarization, pulse shape, south-north asymmetry of pulse amplitudes, etc.) indicate that the radio emission has a different dominant mechanism of generation in air. Nevertheless, by theoretical reasons the shower charge excess should be the principal source of the coherent radio emission in dense media, and after a while interest in the idea of Askar'yan was renewed by the suggestion to detect high energy (HE) neutrinos in cold antarctic ice, which has very low radiowave absorption at temperatures below $-50°$C [2]. It was argued that a radio antenna array placed on the glacier surface in Central Antarctica could provide an effective target volume of the order of $10^9 - 10^{10}$ m^3 for cosmic neutrinos with energies above 100 TeV [2]–[4].

In this paper we make a detailed threshold analysis for such a detector, taking account of radiowave absorption in ice. We calculate as well a production rate of showers initiated

by upward-going HE neutrinos in the upper layer of the Earth. That allows us to estimate an expected neutrino event rate in a radiowave detector from the different anticipated HE neutrino fluxes.

2 Event rate in a radio detector

We consider a radiowave antarctic neutrino detector as a number of downward-looking antennae disposed on several dozen meters triangular grid enclosing a glacier area of the order of 1 km^2. The antennae sample Cherenkov radio pulses from ice, which would provide well-defined conic-type images on the grid (the Cherenkov angle is equal to 56° in ice) [2]–[4].

In general, the radio detector event rate induced by the neutrino flux is given by

$$N_\nu = \int dE_o \int d\Omega \, V_{eff}(E_o, \theta, \phi) p_\nu(E_o, \theta, \phi). \tag{1}$$

Here $p_\nu(E_o, \theta, \phi)$ is the electromagnetic shower production rate per unit volume for a given shower energy E_o and direction (θ, ϕ), $V_{eff}(E_o, \theta, \phi)$ is the effective detection volume.

To make an initial estimation of the event rate we neglect the angular dependence of V_{eff} and use the next approximation:

$$V_{eff} = S[R_{max}(E_o) - R_{min}], \tag{2}$$

where S is the enclosed grid area, $R_{max}(E_o)$ is the maximum detection depth for a given shower energy E_o, R_{min} is the minimum detection depth, which depends mainly on the grid spacing. In this case Exp. (1) is simplified:

$$N_\nu = \int\limits_{>E_{min}} dE_o \, V_{eff}(E_o) P_\nu(E_o), \tag{3}$$

where

$$P_\nu(E_o) = \int d\Omega \, p_\nu(E_o, \theta, \phi)$$

and the minimum detection energy E_{min} corresponds to the minimum detection depth R_{min}.

3 Threshold analysis

A numerical real time computation of the radiowave emission from electromagnetic showers developed in the totally transparent ice [5] gives the following parametrization of the electric field spectrum at the Cherenkov angle:

$$R|\vec{E}(\omega, R, \theta_{\check{C}})| = \frac{0.55 \times 10^{-7} (\nu/\nu_o)}{1 + 0.4(\nu/\nu_o)^2} \frac{E_o}{1 \text{ TeV}} \text{ (V/MHz)}. \tag{4}$$

Here ν is the frequency, R is the distance from the shower, E_o is the incident electron (photon) energy, ν_o = 500 MHz (the result of [5] was divided by 2 to define the Fourier transform as $\vec{E}(\omega) = \int dt \, \vec{E}(t) exp(i\omega t)$).

Radiowave attenuation in the real ice strongly depends on the wavelength, as well as on the ice temperature. Therefore, we have used the original data on radiowave absorption in ice [6] together with the results of temperature profile measurements in a super deep bore hole at the Vostok Antarctic Station [7] to calculate the total attenuation of a shower radio pulse after vertical propagation from a given depth to the ice surface (Fig. 1).

To obtain the threshold energy for the one-channel radiowave detection of electromagnetic showers we need to consider in some detail a process of radio pulse transformations by a receiving antenna and its preamplifier (active filter). The relation between output antenna voltage $V(\omega)$ and incident electric field $\vec{E}(\omega)$ is given by

$$V(\omega) = \vec{R}_A(\omega) \cdot \vec{E}(\omega), \tag{5}$$

where $\vec{R}_A(\omega)$ is the reception transfer function of antenna. As it is recognized, the so-called TEM horn is the most promising broad-band antenna for impulsive field measurements (for instance, see Ref. [8]). Its reception transfer function has approximately constant magnitude and linear phase dependence over the frequency range from a hundred MHz to several GHz. As one can see (Fig. 1), the shower radio pulse spectrum has the same band of wavelengths. Therefore, the TEM horn will produce an output voltage that is a high fidelity replica of the shower electric field in the time domain. For example, the 1×1 m^2 arcsine TEM horn specially designed for the neutrino radiowave experiments has $R_A \simeq 0.14$ V/(V/m) for a normal incident field in air. The reception pattern of this antenna is rather broad with the half-amplitude beamwidths of about 90° in both E and H planes for an incident electromagnetic pulse of 1 ns duration [4].

The conventional definition of a signal-to-noise ratio at the filter output is [9]

$$\frac{S}{N} = \frac{\text{peak instantaneous output signal power}}{\text{output noise power}}. \tag{6}$$

The maximum of (6) occurs when the filter transfer function is proportional to the complex conjugation of the input filter voltage $V^*(\omega)$ ("matched filter"). The maximum value is

$$[S/N]_{max} = \frac{2}{N_o} \int\limits_{-\infty}^{+\infty} \frac{d\omega}{2\pi} |V(\omega)|^2, \tag{7}$$

where N_o is the one-sided white noise power density at the filter input. From (5) and (7) we obtain for the normal incident shower radio pulse received by a TEM horn in ice:

$$[S/N]_{max} = \frac{2}{N_o} \varepsilon R_A^2 \int\limits_{-\infty}^{+\infty} \frac{d\omega}{2\pi} |\vec{E}(\omega, R, \theta_{\check{C}})|^2, \tag{8}$$

where ε is the relative permeability of ice (R_A rises by a factor of $\sqrt{\varepsilon}$ in medium). If the antenna impedance is equal to the load (filter) one,

$$N_o = kT_N Z_L. \tag{9}$$

Here $k = 1.381023$ J/K is the Boltzmann constant, T_N is the noise temperature and Z_L is the load impedance. Using the parametrization (4) and taking into account the radiowave

absorption in ice for vertical pulse propagation from 100 m depth, we find for $Z_L = 50$ Ohm and $\sqrt{\varepsilon} = 1.8$ (ice refraction coefficient):

$$[S/N]_{max} \simeq 0.1 \frac{E_o^2(\mathrm{TeV})}{T_N(\mathrm{K})} \left(\frac{R_A}{0.14 \ \mathrm{m}} \right)^2 . \tag{10}$$

For the signal-to-noise ratio of unity, $T_N = 300$ K (according to the antarctic noise measurements [10]) and $R_A = 0.14$ V/(V/m) the shower threshold energy E_{th} is approximately equal to 55 TeV. This is a factor of 7 lower than the result obtained by Zas, Halzen and Stanev [5]. They performed the threshold estimation for a half-wave dipole antenna adapted for the narrow-band receiving technique of EAS radio detection experiments. Hence, the use of a broad-band TEM horn together with a matched filter result in the significant decrease of the threshold energy.

Fig. 2 shows the calculated dependence of the relative threshold energy on the shower production depth. The related results of the maximum detection depth R_{max} can be parameterized by the expression:

$$R_{max}(E_o) \simeq 615 \ln(1 + E_o/5.8E_{100}) \ (\mathrm{m}), \tag{11}$$

where E_{100} is the threshold energy for the depth of 100 m.

4 Production rate of neutrino-induced showers

Electromagnetic showers are directly produced only by the charged current interactions of electron neutrinos:

$$\begin{array}{ccccccc} \nu_e & + & N & \longrightarrow & e & + & \dots . \\ & & & & \searrow & & \\ & & & & & e.m.\, shower & \end{array} \tag{12}$$

But hadronic showers, which are generated by all the types of neutrino interactions

$$\begin{array}{ccccccc} \nu & + & N & \longrightarrow & l & + & hadrons\, , \\ & & & & & & \searrow \\ & & & & & & shower \end{array} \tag{12$'$}$$

initiate electromagnetic subshowers too through decay of neutral pions and eta particles. According to the accelerator calorimetric experiments and Monte Carlo simulations, the contribution of electromagnetic subshowers to the total energy deposit of hadronic shower increases with the initial hadron energy and amounts to $\sim 90\%$ at $E_o > 10$ TeV [11]. As the mean inelasticity in the reaction ($12'$) is ~ 0.3 for $E_\nu > 100$ Tev [12], one should expect that the power in the radio signal from the neutrino-induced hadronic shower will be only slightly less than the power from the pure electromagnetic shower of the same energy. In the paper we neglect this difference, though the question deserves more detailed study.

The shower production rate $P_\nu(E, \gamma)$ for upward-going neutrinos is defined as

$$P_\nu(E_o, \gamma) = n_N \sigma_o G_\nu^{tot}(E_o, \gamma) \Phi(E_o, \gamma). \tag{13}$$

Here $G_{\nu}^{tot}(E_o,\gamma)$ is the total shower production function, $\Phi(E_o,\gamma)$ is the differential power-law energy spectrum of incident neutrino flux with the integral spectral index γ, n_N is the nucleon number per unit volume; $\sigma_o = 1.1 \times 10^{-34}$ cm^2 is the standard cross section.

The total shower production functions $G_{\nu}^{tot}(E_o,\gamma)$ for electron and muon neutrino fluxes are given by

$$G_{\nu_e}^{tot}(E_o,\gamma) = \frac{\sigma^{cc}(E_o)}{\sigma_o}\Omega_{eff}(E_o,\gamma) + G_{\nu}^{nc}(E_o,\gamma) \tag{14}$$

$$G_{\nu_\mu}^{tot}(E_o,\gamma) = G_{\nu}^{cc}(E_o,\gamma) + G_{\nu}^{nc}(E_o,\gamma) \tag{14$'$}$$

respectively with the definition of $G_{\nu}^{j}(E_o,\gamma)$ ($j \equiv cc$ for the charged current interaction and $j \equiv nc$ for the neutral one) as

$$G_{\nu}^{j}(E_o,\gamma) = \int\limits_0^1 dy\, y^{\gamma}\Omega_{eff}(E_o/y,\gamma)\frac{\partial\sigma^{j}(E_o/y,y)}{\sigma_o\partial y} \tag{15}$$

In these expressions $\sigma^{j}(E)$ is the neutrino-nucleon cross section, $y = (E_\nu - E_l)/E_\nu$ is the relative energy loss of neutrino in the laboratory frame and $\Omega_{eff}(E,\gamma)$ is the effective solid angle for upward-going neutrino flux, which is defined through the coefficient of neutrino absorption by the Earth $k(E,\theta,\gamma)$ as in [13]

$$\Omega_{eff}(E,\gamma) = 2\pi \int\limits_0^1 d\cos\theta\, k(E,\theta,\gamma). \tag{16}$$

Let us notice that the shower production functions $G_{\nu}^{j}(E_o,\gamma)$ are actually the generalization of the neutrino spectrum-weighted moments

$$Z_{\nu}^{j}(E_o,\gamma) = \int\limits_0^1 dy\, y^{\gamma}\frac{\partial\sigma^{j}(E_o/y,y)}{\sigma_o\partial y}, \tag{17}$$

which have been originally calculated in the paper [14], for the case of neutrino absorption. We performed the computations of $G_{\nu}^{tot}(E_o,\gamma)$ by use of the EHQL [15] and DLA [16] parametrizations of the quark distribution functions, as it has been proposed for the neutrino cross section evaluation in [17, 12], and PREM model of the Earth structure [18]. The results for electron and muon neutrino fluxes with $\gamma = 2.1$ are given in Fig. 3 and Fig. 4 respectively.

All the functions $G_{\nu}^{j}(E_o,\gamma)$ vary rather slowly with γ. The behavior of the $\bar{\nu}_e$ shower production function around 6.4 PeV (Fig. 4) is strongly affected by the Glashow resonance reaction

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow all \tag{19}$$

with a very high cross section [19, 20]. The Earth is almost opaque for such neutrinos.

5 Detection of AGN neutrinos

Active Galactic Nuclei (AGN) have long ago been considered as possible cosmic objects for high energy neutrino production [21, 22]. Due to the recent development of the idea in some important ways by Stecker et al. [23, 24] and other authors [25]–[27], nowadays AGN are recognized as most promising sources of HE neutrinos. Therefore, we calculate the expected event rate in a 1 km^2 radiowave detector for the different existing models of AGN neutrino production, assuming $E_{100} = 55$ TeV and $R_{min} = 100$ m (for comparative discussion of the models see Ref. [28, 29]). The results are given in Table 1. The expected background from atmospheric neutrinos [30] will be ~ 20 events per year.

Table 1. Expected event rate for the different models of AGN neutrino production

Diffuse neutrino fluxes from AGN by	**Expected event rates (S/N = 1), year^{-1} km^{-2}**
Stecker et al., 1992	110
Szabo and Protheroe, 1992 (max)	2800
Szabo and Protheroe, 1992 (min)	730
Biermann, 1992	110
Sikora and Begelman, 1992	100

These figures can be compared with the predicted muon event rate in a 10^4 m^2 optical underwater neutrino telescope, such as DUMAND II, NESTOR or NT-200, which are under construction now. According to [29] at muon energies above 1 TeV the rate will be for Ref. [24] ~ 30 per year and for Ref. [25] from 160 to 800, decreasing by several times at 10 TeV. Ultra high energy neutrinos from AGN can be detected by DUMAND II due to the Glashow resonance reaction with the rate for Ref. [24] about several dozen events per year [31].

Fig. 5 shows a plot of rate in a radiowave detector versus signal-to-noise ratio. As one can see, even at high detection thresholds the diffuse AGN flux remains measurable by a radiowave detector for all the models, save the Sikora and Begelman one.

We have estimated the event rate in a radiowave detector only for upward-going neutrino fluxes, though inclined neutrinos from the upper hemisphere would give rise to the event rate too, if some part of initiated Cherenkov radio emission has a direction toward the ice surface. However, these calculations are very sensitive to the particular form of the angular dependence of the effective detection volume and require a full Monte Carlo simulation of the detector response.

Besides of the surface deployment of a radio array, it was proposed also to put antennae deep under the ice in bore holes to detect neutrinos from the upper hemisphere more effectively [32]. Because of the limiting hole size (20$''$ diameter), only small conical antennae are suitable in this case and, therefore, the detection threshold should be several times higher. However, a downward-going HE neutrino flux does not suffer from the Earth shadowing effect and this can partially compensate the event rate decrease, especially due to the Glashow resonance reaction. Some type of a combined detector is possible also.

6 Conclusions

In this paper we have shown that a 1 km^2 radiowave neutrino detector established in Central Antarctica (at the South Pole or Vostok Station) should be sensitive to the predicted diffuse fluxes of AGN neutrinos at energies above a hundred TeV. For some production models AGN neutrinos would be effectively detected in the broad energy region up to 1 PeV, that gives, in principle, a possibility to determine the spectrum shape.

The performed calculations of the shower production rate by upward-going HE neutrino flux are relevant also for the other HE neutrino detection experiments.

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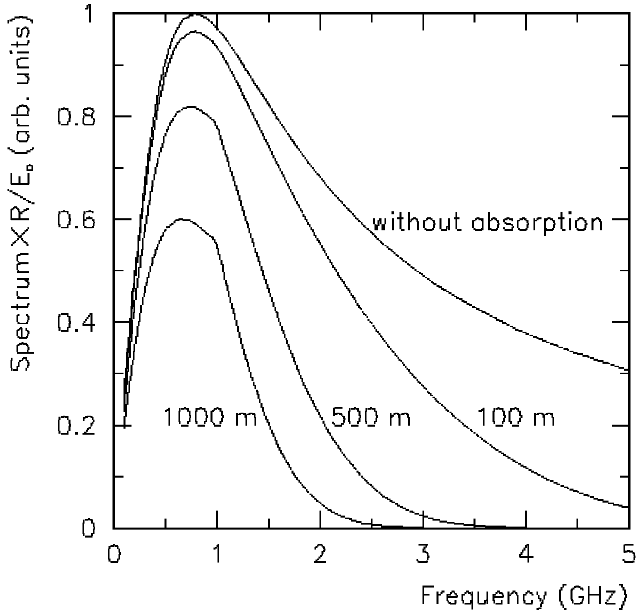

Figure 1: Radio pulse spectrum after vertical propagation from a given depth (the maximum value is equal to 43.5 nV/MHz/TeV).

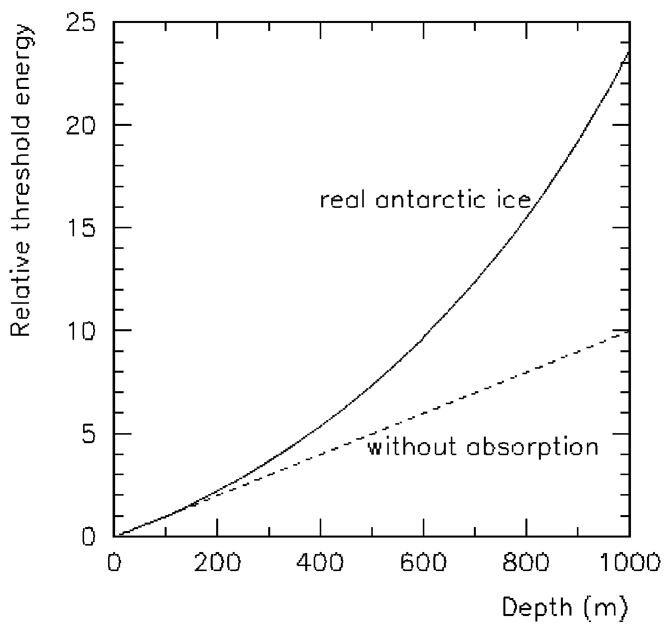

Figure 2: Relative threshold dependence on depth (E_{100} is taken to be unity).

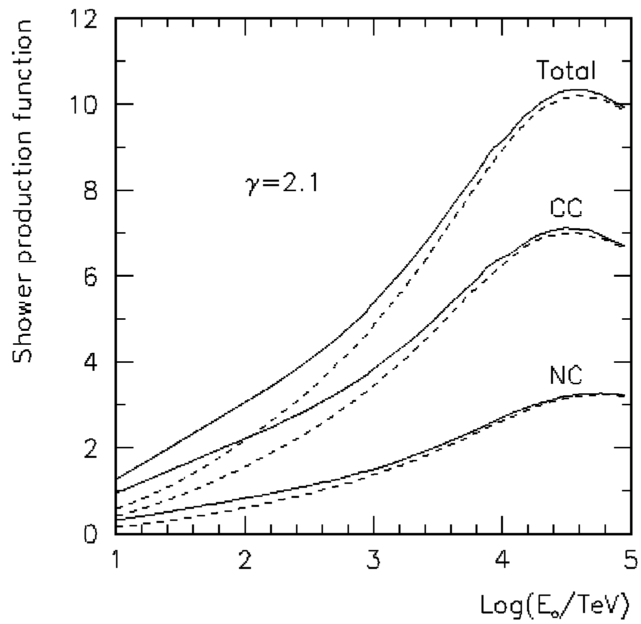

Figure 3: Shower production functions for muon neutrino (solid line) and antineutrino (dashed line). Here CC denotes the charged current and NC the neutral current.

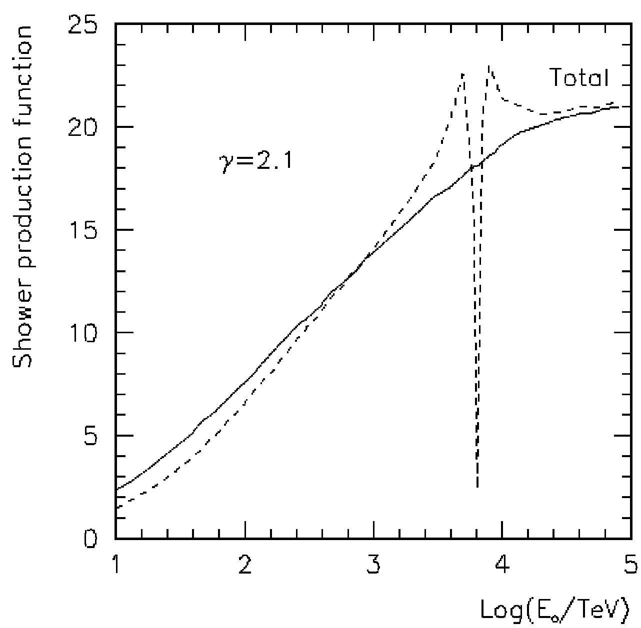

Figure 4: Shower production functions for electron neutrino (solid line) and antineutrino (dashed line).

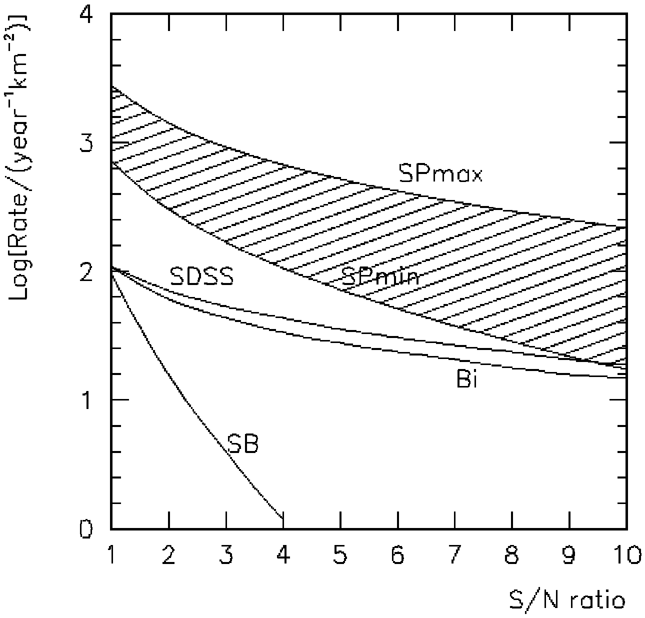

Figure 5: Event rate versus signal-to-noise ratio ($S/N = 1$ for $E_{100} = 55$ TeV) for the different models of AGN neutrino production (SDSS, Stecker et al. (1992); SPmax and SPmin, Szabo and Protheroe (1992); Bi, Biermann (1992); SB, Sikora and Begelman (1992)).